TRANSISTOR HAVING GRAPHENE BASE

CROSS-REFERENCE

[0001] This application claims the benefit of priority based on U.S. Provisional Patent Application No. 61/384,727 filed on Sep. 21, 2010, the entirety of which is hereby incorporated by reference into the present application.

TECHNICAL FIELD

[0002] The present invention relates to a three-terminal junction transistor, more specifically a three-terminal junction transistor having a graphene material base layer.

BACKGROUND

[0003] Three-terminal junction transistors have application to numerous electronic devices, including digital circuits, analog-to-digital converters, digital-to-analog converters, mixed-signal circuit, fiber-optic receivers, and microwave amplifiers.

[0004] A three-terminal transistor has an emitter, a base, and a collector with the base controlling the current transport from the emitter to the collector. Such a transistor can operate as a unipolar transistor having one predominant carrier transport type or as a bipolar transistor having two carrier transport types.

[0005] A unipolar transistor is typically designed to have electrons as the predominant carrier type. In addition, unipolar transistor device structure can be designed so that the carriers are hot electrons within the base of the transistor. If the base is thin, the carriers can have ballistic transport through the base. The unipolar transistor is typically operated primarily in the voltage-control mode with the injection of electrons from the emitter into the base controlled by varying the voltage difference applied between the emitter and base electrodes, with some portion of the electrons injected into the base transporting through the base and being collected by the collector.

[0006] The three-terminal transistor can also operate in a bipolar-mode where the injection of one carrier type (holes) into the base modulates the injection of a second carrier type (electrons) from the emitter into the base with some portion of the electron injected into the base transporting through the base and being collected in the collector. The bipolar transistor is typically operated primarily in the current-control mode.

[0007] The capabilities of these circuits are often rated by the speed of operation of the circuits. The speed of operation of the circuit type that utilizes three-terminal transistors is often dominated by the transit time of carriers through the base layer of the three-terminal transistor. Thus, it is often useful to use a thin base layer to achieve a fast carrier transit through the base layer.

[0008] One measure of the frequency performance capability of a three-terminal transistor is the transition frequency (cutoff frequency), fT, which is strongly dependent on the transit time of carrier through the base of a transistor. The maximum oscillation frequency Fmax for a bipolar transistor is approximately described by the equation

$$F_{max} = \left(\frac{fT}{8\pi RbCcb}\right)^{1/2}$$

where Rb is the base resistance, Ccb is the collector base capacitance, and fT is the cutoff frequency. Thus, the maximum frequency of oscillation is inversely proportional to the base resistance Rb. See Bart Van Zeghbroeck, "Chapter 5: Bipolar Junction Transistors," *Principles of Semiconductor Devices, available online at http://ecee.colorado.edu/~bart/book/book/content*5.htm (downloaded Jun. 15, 2011).

[0009] It has been known for some time that a hot electron transistor (HET), and especially a ballistic transistor, can potentially be operated at frequencies in excess of those achievable with conventional (diffusive) transistors. T. E. Bell, "The Quest for Ballistic Action," *IEEE Spectrum*, February 1986, pp. 36-38. Various types of hot electron transistors (HET) have been proposed. See L. F. Eastman, "Ballistic Electrons in Compound Semiconductors," *IEEE Spectrum*, February 1986, pp. 42-45; A. F. J. Levi et al., "Injected-Hot-Electron Transport in GaAs," *Phys. Rev. Lett.* 55(19), pp. 2071-2073 (1985); M. Heiblum et al., "Direct Observation of Ballistic Transport in GaAs," *Phys. Rev. Lett.* 55(19), pp. 2200-2203 (1985); and M. I. Nathan et al., "A Gallium Arsenide Ballistic Transistor," *IEEE Spectrum, February* 1986, pp. 45-47.

[0010] One type of HET transistor has a thin P-type doped emitter material layer in the emitter transition layer at the emitter/base interface that implements a thermionic emission injection structure, also known as a planar doped barrier or a camel barrier, and a thin P-type collector material layer in the collector transition layer at the collector/base interface that implements a collector barrier, see J. R. Hayes et al., "Hot Electron Spectroscopy," *Electron. Lett.* 20(21), pp. 851-852 (1984); J. M. Shannon, "Calculated performance of monolithic hot-electron transistors," *IEE Proceedings* 128(4), pp. 134-140 (1981).

[0011] Another type of transistor uses tunnel injection and comprises emitter, base, and collector, with an appropriately shaped potential barrier between emitter and base, and a second barrier between base and collector. This second type, which is referred to as a tunneling hot electron transfer amplifier (THETA), differs from the first type in having tunnel injection into the base. See M. Heiblum, "Tunneling Hot Electron Transfer Amplifiers (Theta): Amplifiers Operating Up To The Infrared," *Solid-State Electronics* 24, pp. 343-366 (1981).

[0012] Both of the above types are unipolar, although bipolar HETs have also been proposed.

[0013] Other types of bipolar transistors with thin base layers include a Bipolar Quantum Resonant Tunneling Transistor. See A. C. Seabaugh et al., "Pseudomorphic Bipolar Quantum Resonant-Tunneling Transistor," *IEEE Transaction on Electron Devices*, Vol. 36, pp. 2328-2333; and S. Mil'shtein et al., "Bipolar Transistor with Quantum Well Base," *Microelectronics Journal* 39, pp. 631-634 (2008). This device structure utilizes tunneling potential barriers at the emitter/base interface and the collector/base interface to establish a potential well with distinct allowed energy levels in the base layer. Electrons tunnel through the tunnel barrier at the emitter/base interface, enter allowed energy levels in the